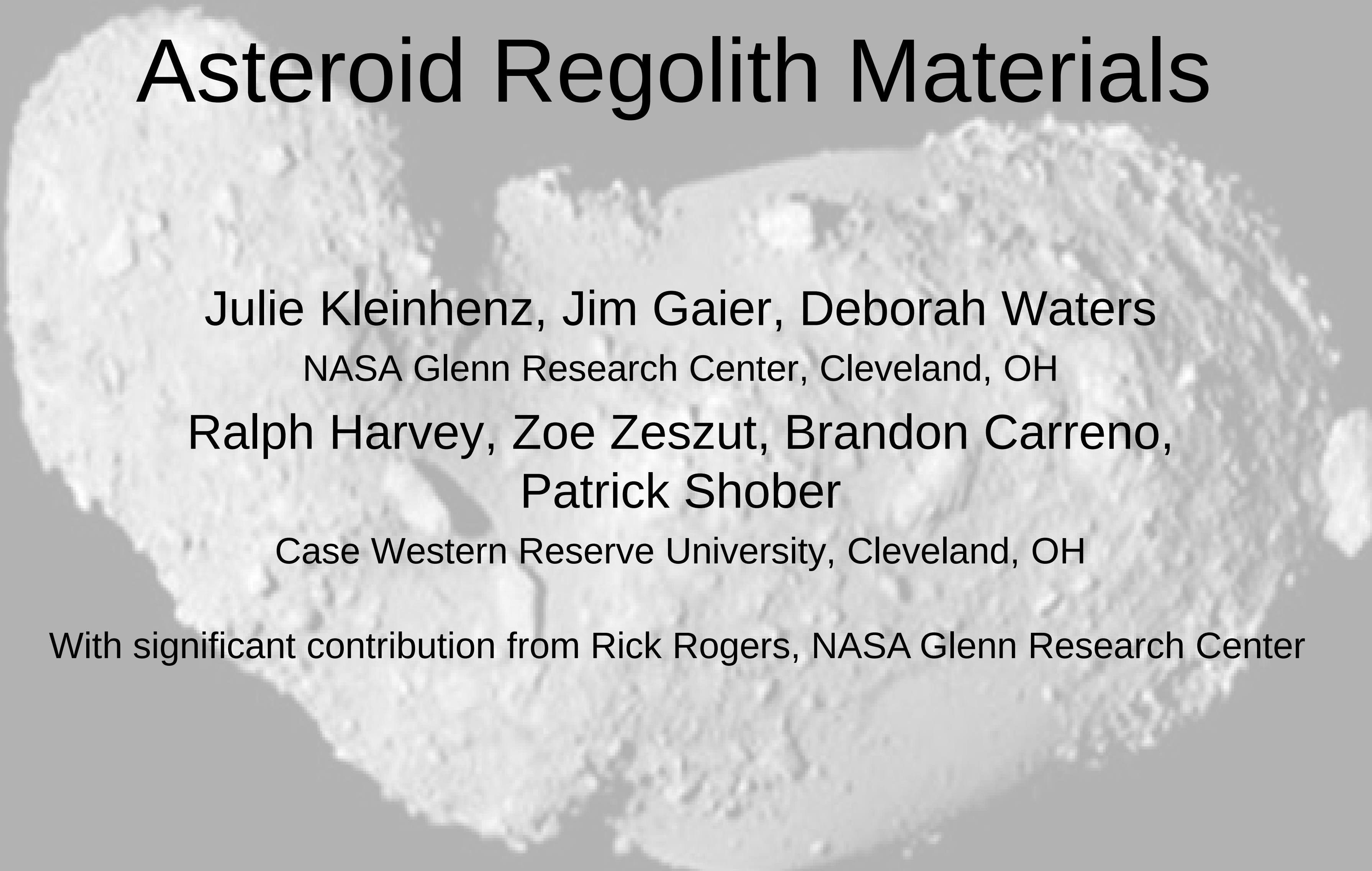
Measurement of Cohesion in Asteroid Regolith Materials



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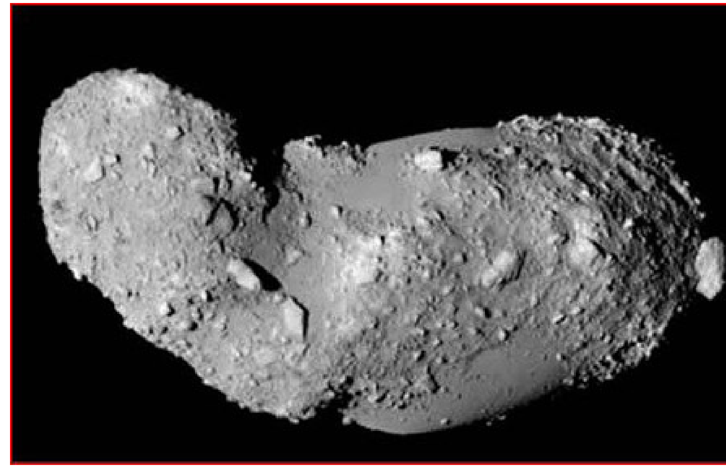
Background

- There is increasing evidence that a large fraction of asteroids, and even Phobos, have such low densities (< 2 g/cm^3) that the are unlikely to be consolidated “rocks in space”.
  - Water is unlikely due to close orbits to the sun.

- Instead, many of these asteroids are thought to be made up of unconsolidated smaller particles of varying size referred to as “rubble piles”. Images of the asteroid Itokawa reinforce this hypothesis.



<u>What holds the rubble piles together?</u>

- Gravitational forces alone are not strong enough to hold together rubble pile asteroids, at least not those that are rapidly spinning
- Van der Waals forces and/or Electrostatic forces must therefore be responsible for holding them together.
  - Previous work suggests that electrostatic forces, which are orders of magnitude stronger are far more likely. Charge build-up is a likely consequence of the interaction of airless bodies with the solar wind plasma, analogous to what has been proposed to occur on the moon.

<u>Objective:</u>

Experimentally measure cohesive forces relevant to those holding rubble pile asteroids together

Cohesion vs Cohesive force

- Cohesive Force = Force to separate two like materials

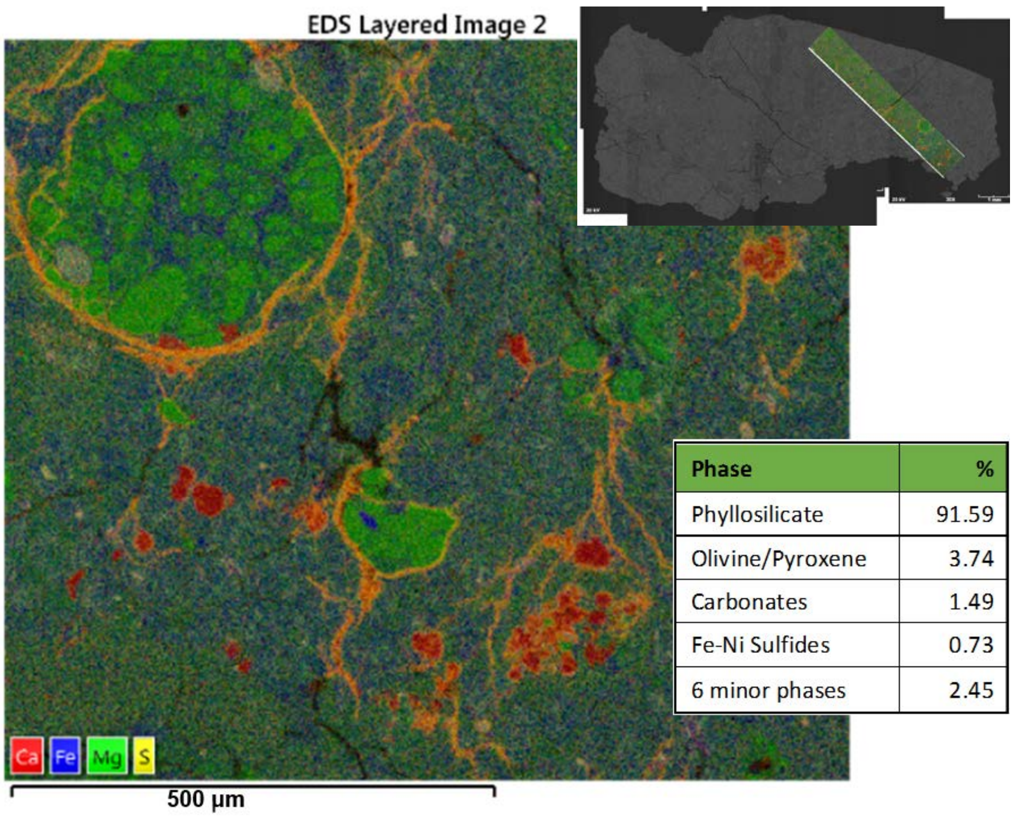
Shear stress
Normal Force
Friction Angle

- Cohesion = Cohesive Stress ($\tau = \boldsymbol{c} + \sigma \tan \varphi$) includes:
  - Capillary forces (when fluids present)
  - Mechanical interlocking
  - Cohesive and Adhesive forces
    - Includes: electrostatic and chemical bonds

- Ultimate goal is Cohesion, but on microscopic level (dust) adhesive/cohesive forces could be substantial

Meteorite Sample

- The primary specimen was a lightly weathered CM2 meteorite obtained from the Antarctic Search for Meteorites program
  - This meteorite is spectroscopically similar to common asteroids, and thought to have representative surface chemistry.
- Cut into thin (~1mm) sections and analyzed using SEM and EDS to determine mineral phases and abundances



Phase	%
Phyllosilicate	91.59
Olivine/Pyroxene	3.74
Carbonates	1.49
Fe-Ni Sulfides	0.73
6 minor phases	2.45

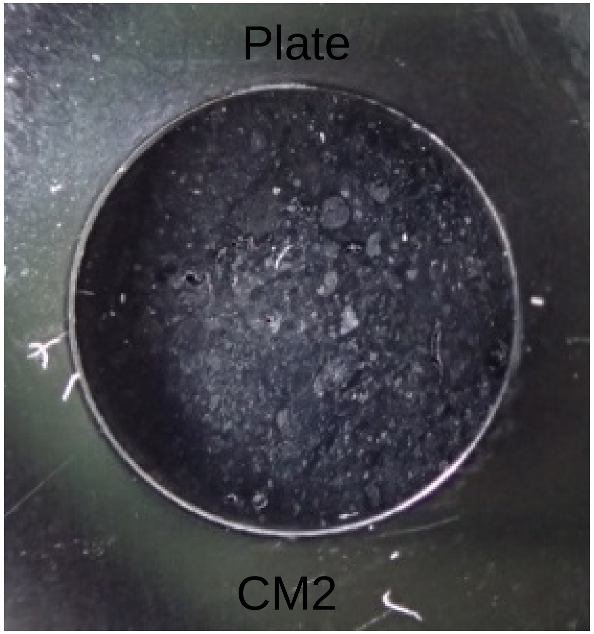
- Four phases identified as significant for cohesion tests
- Dominated by phyllosilicate serpentine $(Mg, Fe)_3Si_2O_5(OH)_4$ matrix
- Olivine/Pyroxene Chondrules make up nearly 4% of the meteorite
- Carbonates and Fe-Ni sulfides significant in some regions
- 6 Minor phases (boron, Ca-Fe sulfides, Ca-Fe oxides, gypsum, Cr-Fe, Al-silicates)

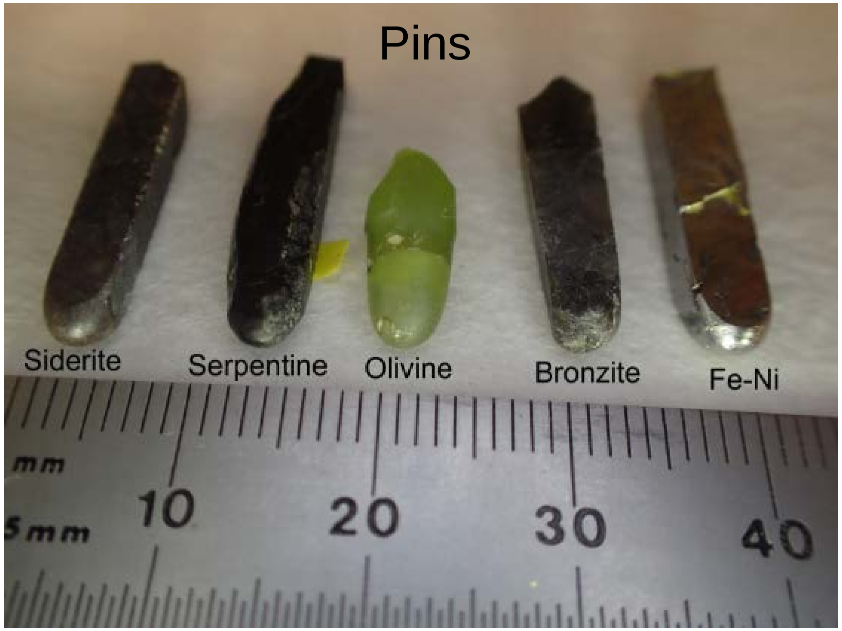
Sample is highly heterogeneous

Cohesive vs Adhesive Force

- Given the heterogeneity of the sample, the nature of the contact force will depend on where contact is made.
- Adhesive force was measured between the meteorite (plate) and samples (pins) composed of primary mineral phase components
  - These Adhesive measurements give a range of possible Cohesive forces that may be present in the asteroid

Mineral	Phase
Siderite	Iron Carbonate
Serpentine	Phyllosilicate
Olivine	Olivine
Bronzite	Pyroxene
Fe-Ni	Fe-Ni Sulfides





Sample Characterization - XRD

- X-Ray Diffraction was performed on powered samples to determine crystallography and average bulk composition of the pin materials
- There was insufficient Olivine to perform this analysis

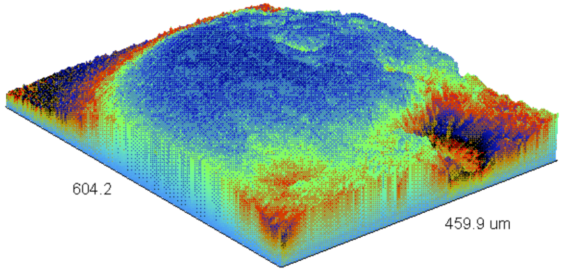
Sample	Phase	Chemical Formula (nominal)	Crystal System	Space Group	wt %* or Relative Abundance¥ (error)
serpentine #2	chrysotile	Mg3Si2O5(OH)4	monoclinic	C2/m (12)	64.1(8)
	antigorite	Mg3Si2O5(OH)4	monoclinic	Pm (6)	22.4(4)
	chlorite	(Mg,F3)6(Si,Al)4O10(OH)8	anorthic	C1 (1)	11.2(3)
	magnetite	Fe3O4	cubic	Fd-3m (227)	2.4(1)
serpentine #3	antigorite	Mg3Si2O5(OH)4	monoclinic	Pm (6)	85(1)
	magnesite	Mg(CO3)	hexagonal	R-3c (167)	11.7(4)
	magnetite	Fe3O4	cubic	Fd-3m (227)	2.3(2)
	periclase	(Mg,Fe)O	cubic	Fm-3m (225)	0.7(1)
bronzite	anthophyllite	Mg7Si8O22(OH)2	orthorhombic	Pnma (62)	54.8(6)
	enstatite	MgSiO3	orthrhombic	Pbca (61)	44.3(6)
	clinochlore	(Mg,Al)6(Si,Al)4O10(OH)8	monoclinic	C2/c (15)	0.9(1)
siderite	siderite	Fe(CO3)	hexagonal	R-3c (167)	97(1)
	low quartz	SiO2	hexagonal	P3221 (154)	3.0(2)
Fe-Ni pin	kamacite	(Fe,Ni)	cubic	Im-3m (229)	major
	cohenite	Fe3C	orthorhombic	Pmna (62)	major
	taenite	(Fe,Ni)	cubic	Fm-3m (225)	minor
	schreibersite	(Fe,Ni)3P	tetragonal	I-4 (82)	minor

* For powdered samples the number in this column refers to weight percent (wt%)

¥ For solid samples (Fe-Ni) the number in this column refers to relative abundance

Adhesion Measurements: Methods

- Pins were machined (cut, shaped, polished and cleaned) to be ~1in long, 1/8 diameter with a rounded tips end to minimize contact surface area
  - The rounded end, combined the a 4 dof movement capability of the pin translator allows the pin to contact with the plate at multiple points and at multiple angles
  - Ideally the end would be hemispheric, but natural minerals are brittle with inherent crystal structures that results in irregularities during machining
- The CM2 plate was cut using a diamond saw to be ~1 mm thick and 10 mm square. The sample holder exposes a ~6mm diameter orifice
- An optical profilometer was used before and after testing:
  - Identify surface roughness and determine if sample were sufficiently polished
  - Characterize surface features and irregularities that may play a role in contact area during adhesion test
  - Determine (post-test) if any material had been transferred between pin anf plate

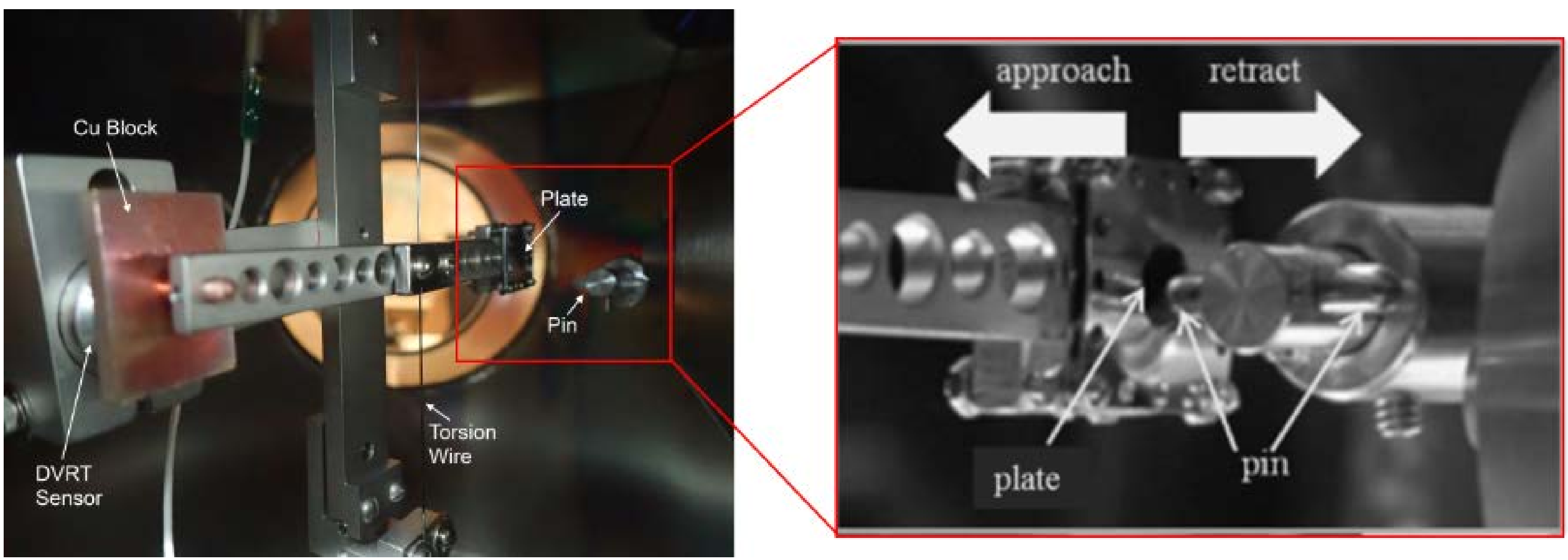


Ultrahigh Vacuum Chamber

- All adhesion measurements took place in an Ultrahigh Vacuum (UHV) chamber, pressures $\leq 10^{-10}$ Torr
- Equipped with combination of ion, sorption, and sublimation pumps
  - Oil free pumps
- Samples were ion cleaned in argon environment at 10^{-5} Torr until scans with a Auger Electron Spectrometer showed significant reduction in Carbon
- Entire rig mounted on a Vibration Isolation table

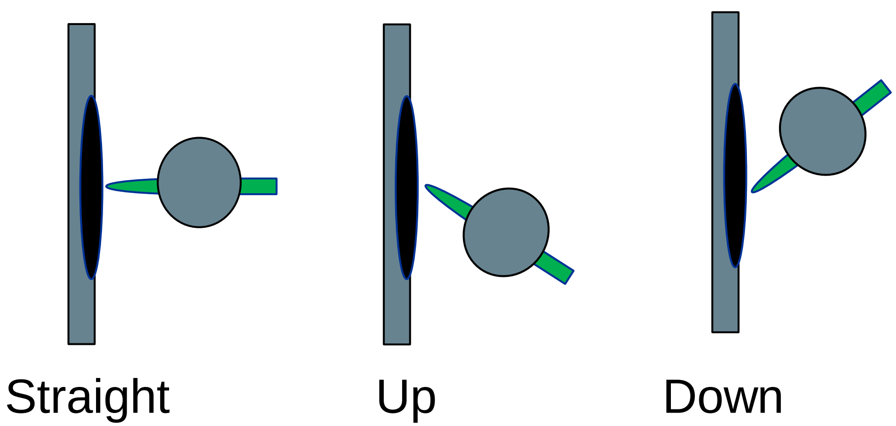
Torsion Balance

- Torsion wire suspending a bar with plate at one end and sensor at the other
- Pin contacts the plate using a 4 dof mechanically actuated arm
- Spring force of the wire in equilibrium with applied force.
  - Angle of bar deflection, along with the spring constant of the wire and bar length, can be used to calculate the applied force
- Sensor is a non contact Differential Variable Reluctance Transducer (DVRT). The sensor noise was approximately 5 μN
  - Data is recorded to Labview® at 200Hz and analyzed using IGOR Pro®

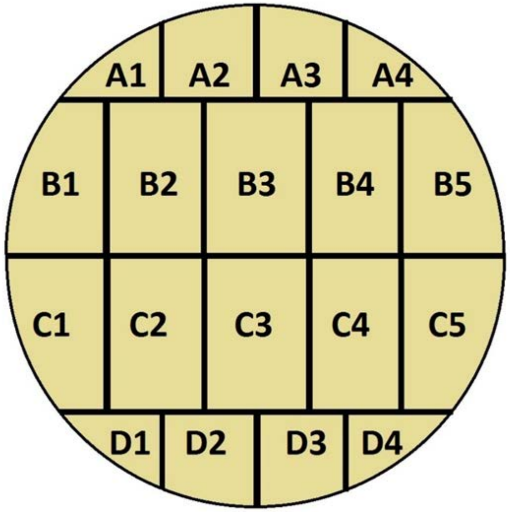


Procedures

- Load pin against plate with a force on order ~1000 μN and remain in contact with plate for ≥30s
- Retract pin from plate at rate of ~9 μm/s
- ~150 runs per test encompassing 18 positions across the CM2 sample surface and 3 pin angles.



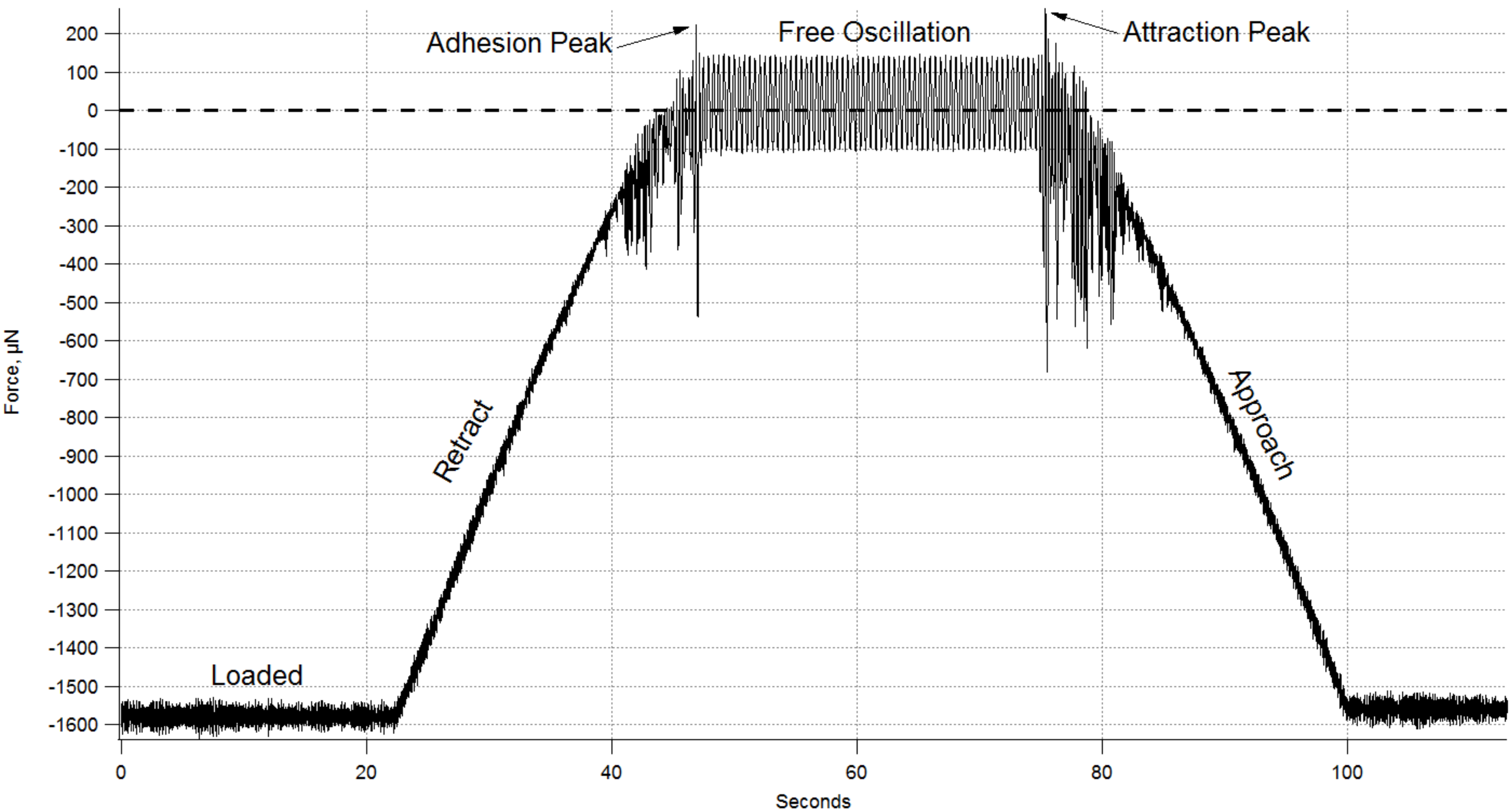
Pin Angles



Notation of Positions on Plate

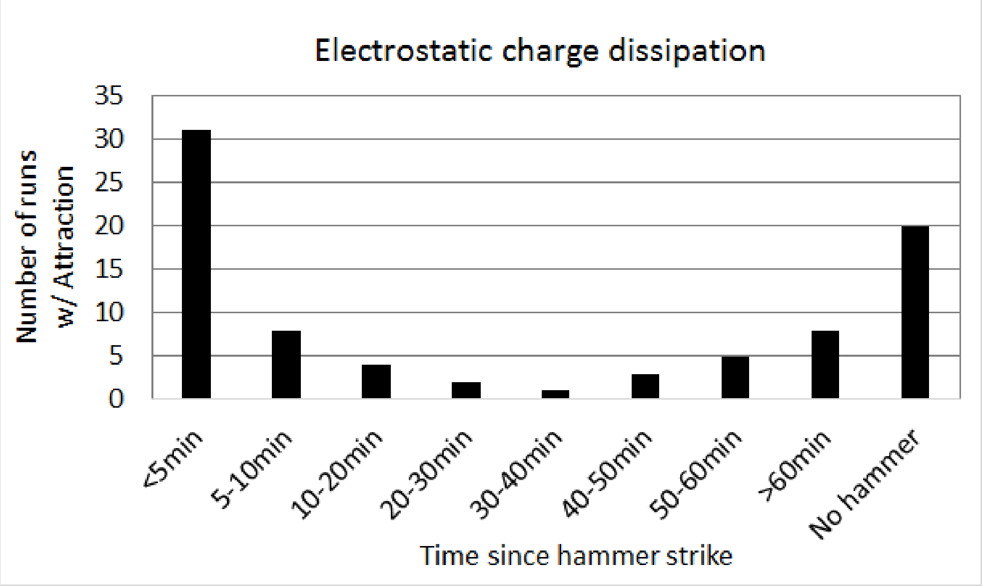
Adhesion Data

Negative force = loading pin against plate
Positive force = pull off



Definition of Forces

- Adhesion Force = Result of retracting the pin away from the plate.
  - Could be due either to electrostatic charge or Van der Waals
- Attraction Force = Results of moving the pin toward the plate after they had been fully separated
  - Results of electrostatic charge. Van der Waals forces do not operate over these distances
- Electrostatic charge induced by:
  - Ion cleaning of the pin
  - Induced by impacting the pin against the plate over a short gap
  - Ion Pump?



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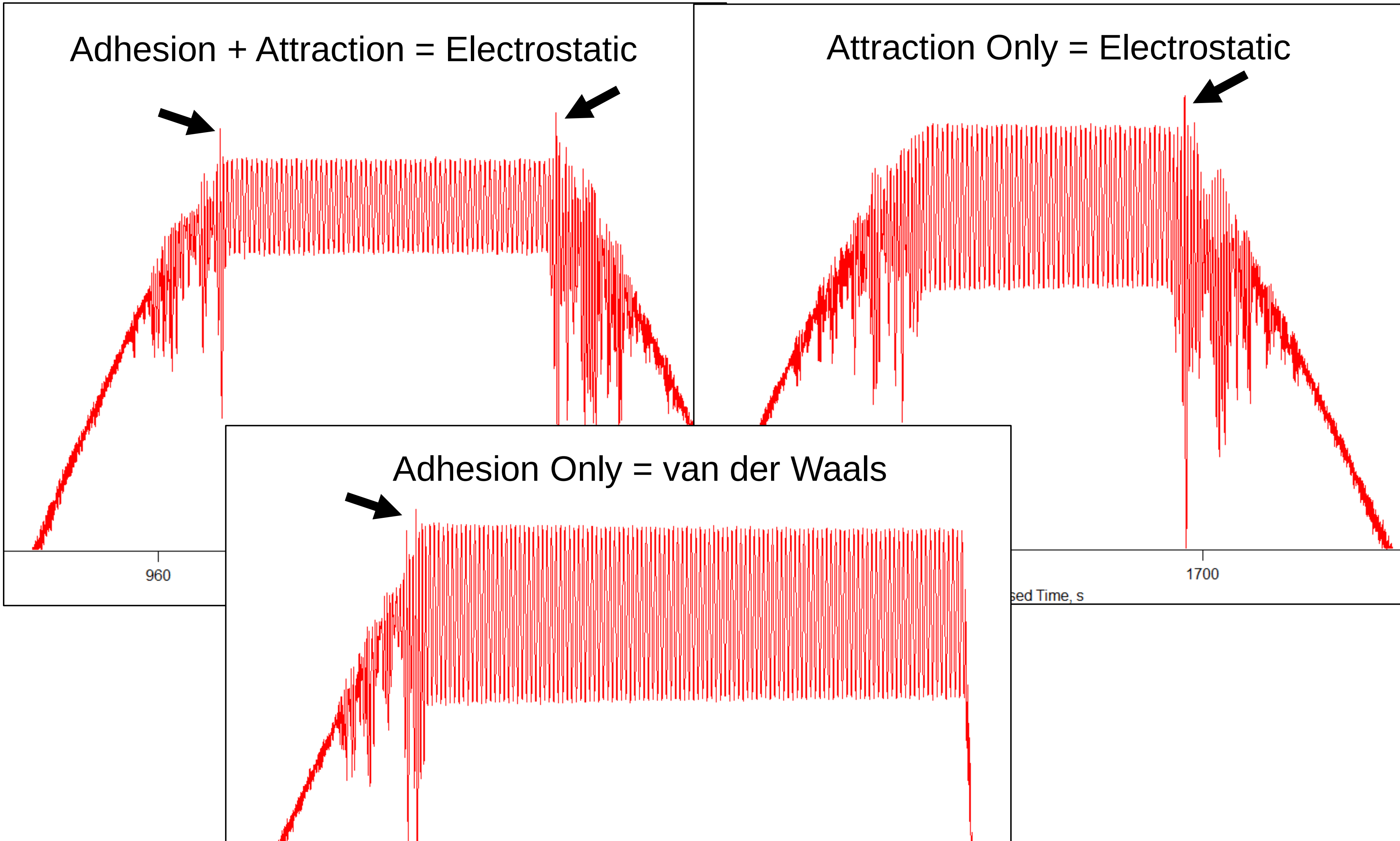
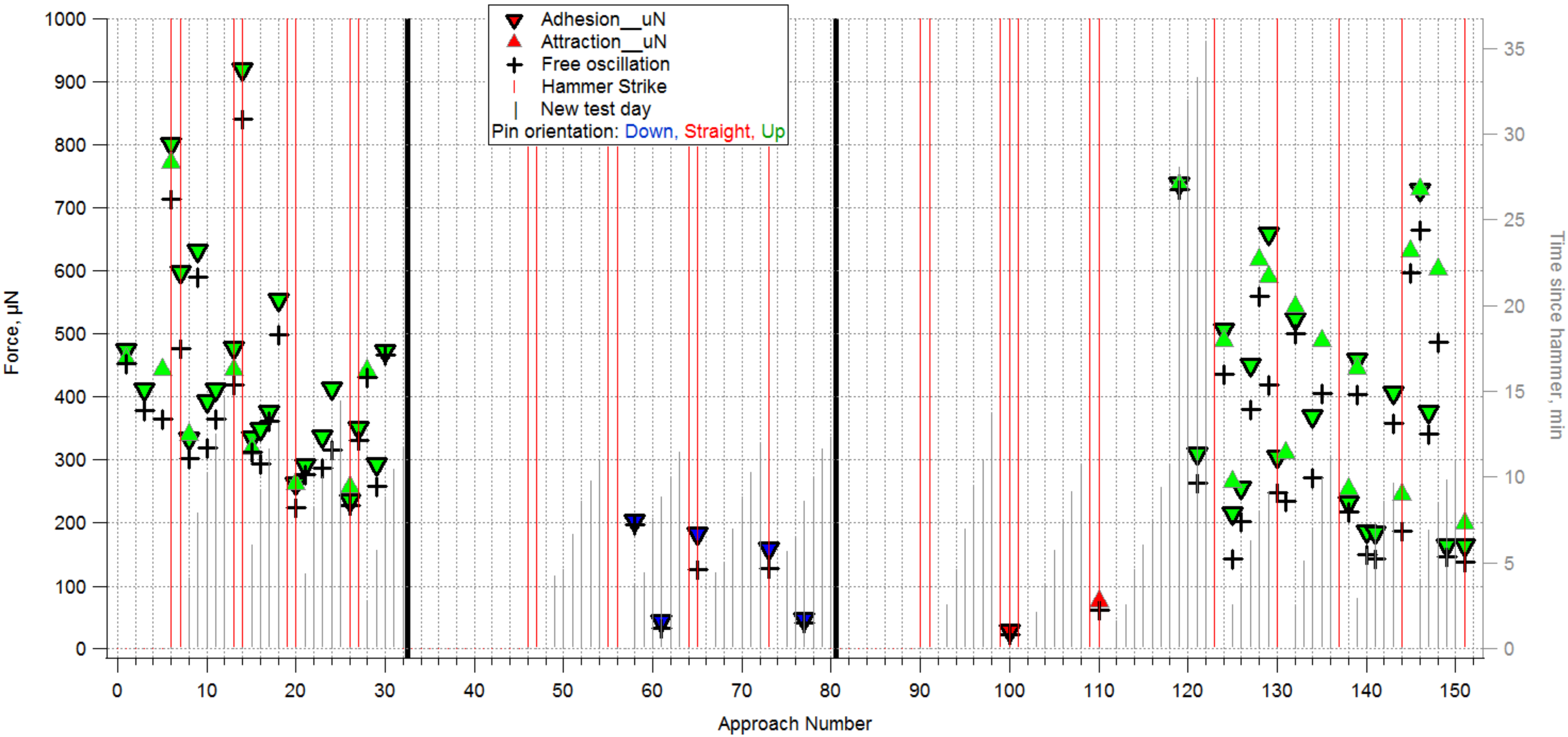


Adhesion Results - Serpentine



- Note dependency on pin orientation

Results Summary

- Only runs with adhesion-only can be a result of Van der Waals forces. Runs with evidence of attractive force must be assumed to have the presence of electrostatic charge.
- A hierarchy was established regarding which material exhibit stronger forces. Serpentine is the most representative of a true “cohesive” force since it comprises 90% of the CM2 meteorite
  - Serpentine > Siderite > Bronzite > Olivine ≈ Fe-Ni

	Serpentine	Siderite	Bronzite	Olivine	FeNi	All Tests
Total number runs	154	144	157	184	136	775
Run with Adhesion	30.5%	14.6%	10.8%	3.8%	2.9%	12.4%
Runs with Attraction	15.6%	14.6%	11.5%	4.3%	8.1%	10.6%
Runs w Adhesion only	20.8%	10.4%	6.4%	3.8%	2.2%	8.6%
Runs with Attraction only	5.8%	10.4%	7.0%	4.3%	7.4%	6.8%
Runs with adhesion & attraction	9.7%	4.2%	4.5%	1.1%	0.7%	4.0%

Open Questions

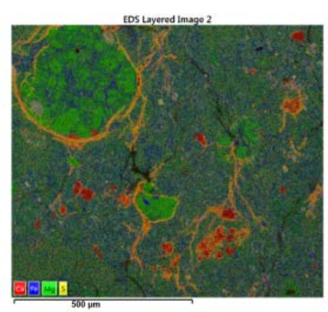
- The majority of runs do not have any defined adhesive/attractive forces, this may be a result of an overly conservative analysis
  - To register, the adhesive/attractive force must be >5 μN greater than the free oscillation. However, the magnitude of free oscillation may be an indicator of force potential
- Electrostatic charge is clearly present even when not intentionally induced. The sources and discharge of these forces is not fully understood.
  - Some runs have attraction with no adhesion, this seems unlikely if the electrostatic charge were already present. (should only be possible if induced ‘hammer strike’ failed to cause adherence)
- Consider surface area affects looking at shape of pin head and roughness using the profilometry results.

Conclusions

- Adhesive Forces on the order of 50 – 400 µN (±35 µN) where measured using the experimental set up and relevant asteroid materials
- Electrostatic forces can be distinguished from Van der Waals forces based on the experimental conditions
  - However, more analysis work is required to fully interpret the data
- The materials used to represent the CM2 mineral phase components exhibited clearly different adhesive strengths:

Serpentine > Siderite > Bronzite > Olivine ≈ Fe-Ni

(Phyllosilicate > Carbonate > Pyroxene > Olivine ≈ Fe-Ni Sulfides)



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Forward work

- Examine properties of powered material to determine optical and thermal properties
  - UV-Vis-NIR spectrophotometer
  - FTIR
  - Characterize transport, thermal and optical degradation of dust material; similar to what was done in previous work with lunar regolith
- In-depth analysis of adhesion results, addressing open questions
- Additional cohesion data using the CM2 plate and new pin samples including:
  - CM2
  - Chondrules